Trieste, 2023, November 22nd

Dear Editor,

Please find attached our revised manuscript titled "**GNSS time series and velocities about a slowly convergent margin processed on HPC clusters: products and robustness evaluation**", for publication to Earth System Science Data as data description paper.

We follow your advice about the location of the dataset, and we move it into the Zenodo repository. In this way, the dataset will have the DOI 10.5281/zenodo.8055800 on Zenodo (DOI number is, for now, assigned as "reserved", but it will be definitive after the acceptance of the manuscript) and each of the compressed archives uploaded is characterized by its own md5 checksum code, which guarantees for its consistency. As a consequence, the reviewed version of the manuscript cites, accordingly, that the dataset is available into Zenodo with the DOI 10.5281/zenodo.8055800.

We follow the advices of the two anonymous Reviewers and we carefully revised the main text, and modified four figures. The answers to the Reviewers' comments are attached below. In order to provide a more complete overview of the results, in addition to the suggested figures' modifications, we also add a new panel to Figure 10 (current panel (d)) to show the zoom of the estimated velocity field in NE-Italy in the vertical component, not only in the horizontal components as in the previous version of the manuscript.

As the previous version of the manuscript, all the authors are aware of the submission of this revision to this journal. This manuscript has not been published previously, nor it is under consideration by other journals.

Hoping that the paper is appropriate for publication in Earth System Science Data, we are looking forward to hear from you.
Please let us know your decision at your earliest convenience.

Best regards,

Sincerely,

Lavinia Tunini

Seismological Research Centre (CRS)
National Institute of Oceanography and Applied Geophysics (OGS)
Borgo Grotta Gigante n. 42/c, 34010 Sgonico (Trieste) - Italy
and
Via Treviso 55, 33100 Cussignacco (Udine) -Italy

e-mail: ltunini@ogs.it

Answers to Reviewer #1 –
Lines' numbers refer to the original version of the manuscript.
The proposed modifications to the manuscript reported in the answers may have been modified after the second Reviewer comments and consequent manuscript revision

The manuscript submitted by Tunini et al. describes GNSS processing for station networks in Italy. While the topic is of general interest and fits the journal's scope, I see serious issues with the current draft. From a geodetic point of view, I like to ask the authors to revise the paper carefully. There are several issues with using geodetic terminology and common geodetic knowledge. Moreover, I found several inconsistencies and wording issues that have to be clarified. Finally, the authors report lengthy technical details clearly specified in different guidelines, these paragraphs should be rewritten in a much shorter way. Overall, I'm in favor of recommending the paper for publication after some general editing.

We thank the Reviewer for the constructive comments and suggestions. We shall revise the manuscript accordingly, and we address the comments as follows.

Detailed comments:

L10 please re-phrase "take the most from ..."

We shall reformulate the sentence as follows: "North-East Italy is a tectonically active region located in the northernmost sector of the Adria microplate, slowly converging with the Eurasia plate, characterised by low deformation rates and moderate seismicity. It greatly benefits from continuous and high-precision geodetic monitoring …"

L25 please re-phrase "GNSS provides a", strictly spoken GNSS provides some navigation signals to the users ....

We shall reformulate the sentence as follows: "The Global Navigation Satellite System (GNSS) allows obtaining a globally-extended positioning dataset which is .."

L27 what is "GNSS technology"?

We agree that the sentence is currently misleading, therefore we shall substitute "GNSS technology" with "GNSS system"

L30 what is a GNSS sensor, I guess you are referring to the antenna?
L31 you can determine sub-mm positions just from one day, I guess you are referring to time series? You might add clock corrections to the precise orbits

Comments on lines 130 and 131. We agree with the Reviewer that the sentence was inaccurate, therefore we shall modify it as follows: "The well-known GPS, combined with GLONASS and the more recent Galileo and Beidou constellations, can provide velocity estimates of the GNSS stations with precisions less than 1 mm/yr when long time-series, precise satellite orbits, and stable monuments are available at the stations."

L40 ff There is no need to explain why you processed the data individually. However, please cite NGL in a proper way and re-phrase "tune" by "customize"

We shall modify the sentence and the NGL citation as follows, hoping that so it is correct: “Nevada Geodetic Laboratory (NGL) (http://geodesy.unr.edu/; Blewitt et al., 2018)”

L44 "beginning of the century" means "early 2000s"?
L57 XX century = 20 century?

Comments on lines 44 and 57. Yes. We shall correct the sentences.

L61 15-20 km is the spatial resolution (or the station distance) but not the scale. "A more" sounds wrong?

We shall rephrase the sentence as follows: “It currently includes 22 permanent GNSS stations located at distances of 15-20 km from each other in most parts of the region, most of which have been in operation for more than 15 years ..”

L66 what do you consider as positions? Do you distinguish between coordinates and positions?

The Reviewer is right, positions and coordinates are here synonymous, therefore we shall rephrase the sentence accordingly.

Fig 2 check the wording

ok.

L105 references for ITRF2014 and IGS are missing

We shall add them, thank you.

L111 "tens of data" -> "tens of stations"?

Yes. We shall correct it.

Fig3 could you explain the drop in 2013?

The drop has been caused by a sudden restriction of the access to several stations located in Slovenia. We shall add this information in the text.

L130 please shorten this part, these are common geodetic standards

ok. We shall shorten the text accordingly.

L143 "log sheets" -> "sitelogs"

ok. We shall correct it throughout the manuscript.

L149 Please rephrase "piece of information ..." + shorten this part, you don't need to report the IGS site guidelines (just cite them)

ok. We shall modify the text as suggested.

L202 language check for "that implements"

ok.

L212 you are using a Helmert blocking approach (clustering) which is very useful

Right, the procedure that we adopted allows us to efficiently reduce the computational times.

L215 Honestly, I don't understand the issue with these old receivers. Are these cross-correlation receivers?

Initially we thought that the problem was due to the old receiver types but we verified that the problem persists also with the new receivers installed recently. Therefore, it seems an issue related to the way the network manager generates the RINEX. After many attempts, we managed to process the data coming from these stations using LC_HELP function of GAMIT/GLOBK. Anyway, we continue investigating how to solve this problem.

We shall modify the text accordingly.

L221 in terms of orbits you should not write "fixed to ... values", they are introduced apriori (the fixing is obvious if you don't estimate orbits). However, a reference is missing here.

ok. We shall modify the sentence, and add the reference.

Tab1 2nd order ionosphere is corrected using the IONEX, please re-phrase; what's about other non-tidal loadings; I miss the orbit & clock products here; please add the estimated parameters and their characteristic here

We shall rephrase the sentence on IONEX files ("2nd-order ionosphere corrected through IGS IONEX files"), and we shall add the missed parameters/products (precise orbits and navigation files with the clock information).

L235 I guess this sentence is about the datum definition. Please explain clearly what was done and why.
L244 what's the meaning of "combining"? Are you stack normal equations?
Comments on lines 235 and 244. We shall revise section 3 to clarify our procedure. In particular, we shall rewrite the part concerning time series calculation and velocity estimation as follows.

"To obtain the position time series, we use the GLOBK module to combine the daily loosely constrained solutions of the subnetworks in a single daily solution leaving the constraints free. Since we want to express the solutions in the International Terrestrial Reference Frame (ITRF14/IGS14 by Altamimi et al. 2016; in particular, we use the newer GNSS geodetic

reference frame IGb14), we then apply generalised constraints (Dong et al., 1998) using the glorg program. For this purpose, we use a six-parameter Helmert transformation (translation and rotation) estimated by minimising the difference in the positions of a set of stations with well-defined coordinates and velocities (reference sites) as a priori coordinates.
The time series are visually inspected to identify offsets that are not due to equipment changes or earthquakes. We automatically remove outliers using two criteria similar to those used by Floyd et al. (2010). First, we remove the daily positions that have formal uncertainty greater than 20 mm. Then we fit the time series to a model consisting of a linear trend and offsets through a weighted linear regression by using the tsfit program. The positions with residuals greater than three times the weighted root-mean-square (RMS) value of the fit were also removed. Finally, we estimated random walk values for each station from the analysis of the outlier-adjusted time series and identified some stations to remove due to noise level (random walk value greater than 2.0 mm2/year) by applying the real_sigma algorithm (Floyd and Herring, 2019), which allows accounting for temporal correlations in the data.
To compute the velocity field, we use the GLOBK program which uses the full variance-covariance matrices contained in all the daily loosely constrained solutions via Kalman filter. Following Herring et al. (2016), from the analysis of the previously generated time series, we retrieve the list of outliers to be excluded from the computation and the site specific parameters to model the stochastic noise on the station positions. To express the velocity solution in other reference frames (e.g., ETRF14, Altamimi et al., 2017), we estimate rotations and rotation rates independently of the EOP, as they are not included in the GAMIT solutions. To reduce the computation time, we divide the stations into sub-networks using netsel. We use a nominal number of 90 stations for each sub-network and the noise model obtained from the time series analysis. First, we estimated the velocities and positions of the included stations for each sub-network. Then, we combine the solutions obtained for each sub-network in a single solution expressed in IGb14. Finally, we recalculate the time series and velocities using the values obtained in the previous iteration as a priori coordinates and expand the list of reference stations to include all stations with random walk values of less than 0.5 mm2/yr. As reported by Herring et al. (2018), the time series that best represent the final velocity solution are those computed considering all stations in the solution as reference sites. We also express our solutions relative to the Eurasia plate as defined by Altamimi et al. (2017) plate motion model (ETRF2014)."

L251 usually we call them "datum sites" or "datum stations", the term "stabilization sites" might be a bit outdated

We shall substitute, throughout the manuscript, "stabilization sites" with the term "reference sites" to clarify the concept.

Fig6 there are well-known assessments of computation time regarding number of stations, you might reference related publications

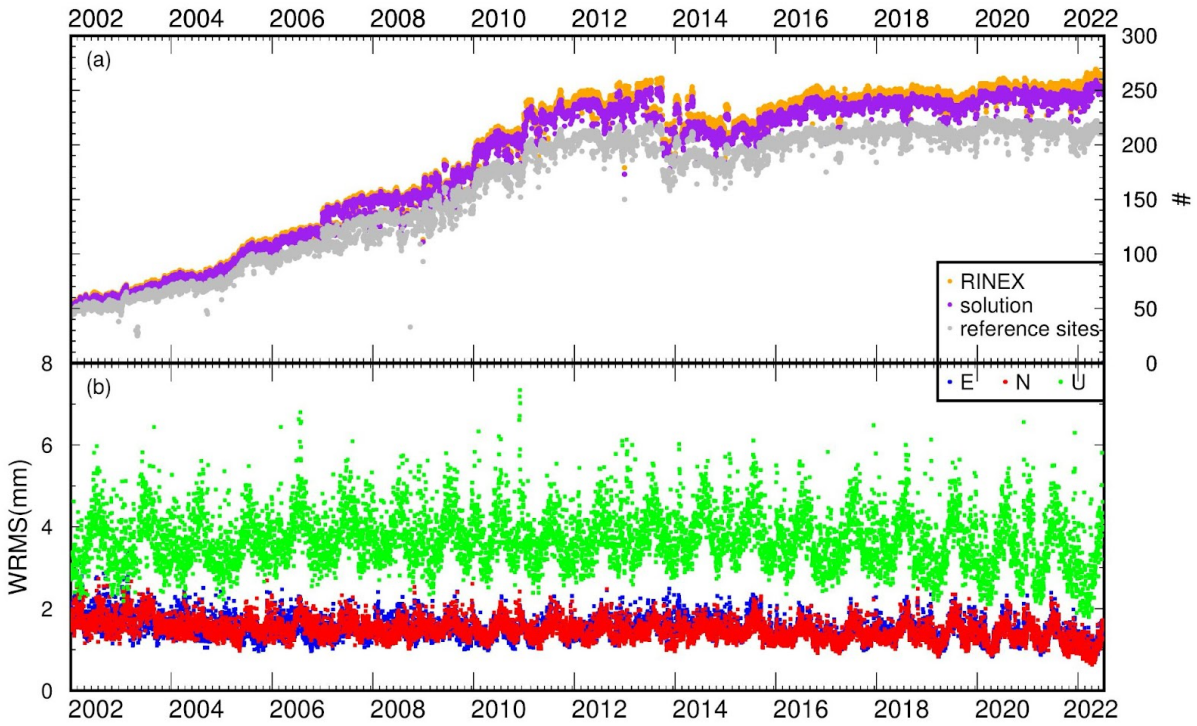
This Figure shows the performance of the HPC infrastructure (GALILEO100) that we used to process the data.

Fig7 what is "stabilization", if these are the "datum stations" you are going to constrain most of your stations. Is there any reason for doing this? Usually, you estimate stations in the area of investigation as free as possible …

"Stabilization sites" are the reference sites used to define the reference frame, i.e., the datum. In order to avoid misunderstandings, we shall explain the term "reference sites" in the text and use it throughout the manuscript.

We shall also modify the Section “3 Data Processing” in order to clarify the calculation of the time series and the velocity estimation (see the text reformulated in the answer to the comments on line 235 and 244). As written in the text, the velocity and time series estimation is performed iteratively. First, using only a subset of reference stations, then using all the stations of the velocity solutions as reference sites. As reported by Herring et al. (2018), the time series that best represent the final velocity solution are those stabilized with all of the stations in the solution.

Fig7 shows the number of reference sites resulting from the last iteration. We modified the legend accordingly. We attach the new Fig7.



L297 what are stabilization errors?

We shall revise the sentence.

L312 I don't understand the consideration of velocity biases. I don't think this is used in Blewitt and Lavallee, 2002. Why do you cite Masson et al 2019 in this regard?

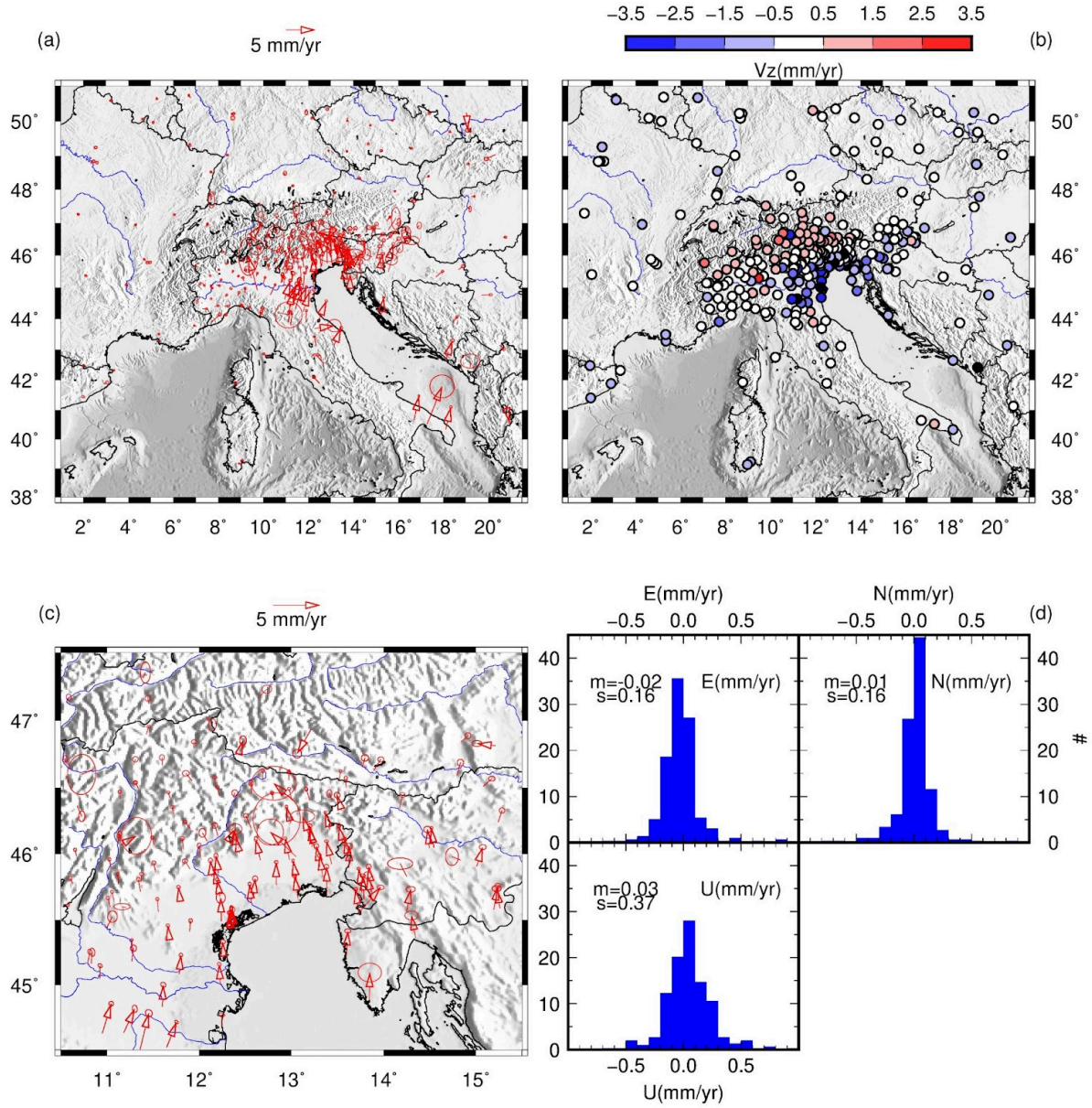
The paragraph deals with the velocity accuracies that can be estimated from the time series. Blewitt and Lavallee (2002) deals with the annual signals affecting the geodetic velocities, therefore, we think it is appropriate to be cited. We also cite Masson et al. (2019), since they continued the work using more recent data and longer time series.

L320ff We might have new stations but they are not young. Language check for "between others, we cite"

ok. We shall correct the text accordingly.

Fig 10 remove topography from these plots, are you showing vz (velocity in z direction)? Overall, you are assuming uncorrelated coordinates in the velocity determination?

We think that topography helps to correctly locate the geodetic stations, therefore, we decided not to remove it completely. However, with the aim to make the Fig10 clearer, we shall diminish the topography shadows contrasts everywhere, and we shall remove minor rivers from Fig10a and Fig10b. We hope that the Reviewer agrees with these changes. We attach the new Figure 10.



Yes, Figure 10b is showing the vertical component of the estimated velocity.

We shall clarify in section 3 that we compute the station velocities by using the full variance-covariance matrices contained in all the daily loosely constrained solutions via Kalman filter implemented in the GLOBK module (see the text reformulated in the answer to the comments on line 235 and 244). Hence we are not using uncorrelated coordinates for the velocity estimation

L370 the difference between VMF1 and GMF was done by many colleagues, refer to their studies. It's kind of useless to skip ocean tide loading, I recommend to remove this part.

ok. We shall modify the text and add new references.

L391 What are "time changes in the environment"

It was a typo. We shall correct it.

L412 What is "variable atmospheric noise"?

We shall rephrase the sentence.

Answers to Reviewer #2
Lines' numbers refer to the original version of the manuscript.

The paper illustrates the analysis strategy of GNSS data in the eastern portion of the Alpine arc, including a broad network of permanent stations. The procedures are well reported and the results are significant and valuable for tectonic studies and slow deforming processes investigations. All the outcomes are publicly available and well documented. I would strongly recommend the publication with only a few minor revisions and a general english editing to enhance readability.

We thank the Reviewer for the interest and for the constructive comments. We revise the manuscript accordingly, and we address the comments as follows.

Detailed comments:

Minor revisions:

Row 79-81: This sentence is rather generic and does not give details on your approach. I would suggest to either delete it or to better explain some terms, i.e. what kind of "slight bias" or "parameter" may compromise the quality (define which one). Or focus on your particular choices that should minimize the error sources.

We shall remove this redundant sentence and move the previous one at the beginning of the last paragraph of Section 1 "Introduction".

Row 198-199: It is not clear if the data processing considers only GPS observations or if it includes other constellations. Please detail this here.

We shall specify that we process GPS data.

Row 215: What does "old receiver" mean? Are they single frequency receivers? Please add more details.

These stations are equipped with double frequency receivers. Initially we thought that the problem was due to the old receiver types but we verified that the problem persists also with the new receivers installed recently. Therefore, it seems an issue related to the way the network manager generates the RINEX. After many attempts, we managed to process the data coming from these stations using LC_HELP function of GAMIT/GLOBK. Anyway, we continue investigating how to solve this problem.
We shall modify the text accordingly.

Row 233 and 378: The Helmert transformation as proposed by the authors is rather peculiar, not alligned to EUREF standards in which only no-net-translations are imposed, please justify your choice.

To obtain position time series (Reviewer' comment on row 233), we use both translation and rotation (instead of only translation), as done in recent studies from Herring et al. (2016) and

Serpelloni et al. (2022). We do not explicitly use scale to avoid potential absorption of height signals.
However, we made a further test using just translation, and results show negligible differences in the time series (see Figure below), with a standard deviation of the order of 0.1 mm in the horizontal components and of 1 mm as a maximum in the vertical component. Furthermore, the RMS of the time series also shows no significant variations when using or not the rotation in the reference frame realization. This further proves the robustness of our solution.

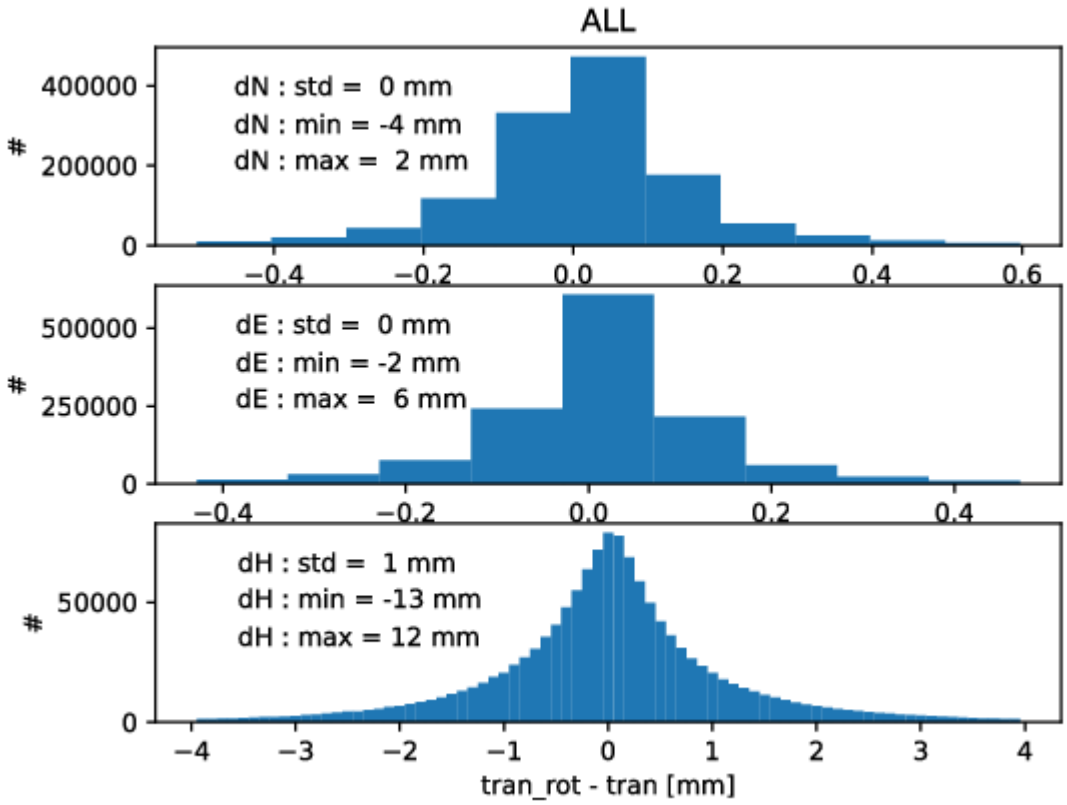


Figure: histogram of the differences between the daily position of all sites computed with translation and rotation and the daily position computed only with translation. The differences are shown for each of the components: from above to the bottom: N, E, and Up.

Regarding the velocities computation, as reported in the EUREF documentation (available at the link https://epncb.oma.be/_productsservices/coordinates/#methodology) "*The EUREF reference frame solution is a multi-year position and velocity solution computed with the CATREF software (Altamimi et al., 2007). The positions and velocities are aligned to the IGb14 reference solution under minimal constraints using 14 transformations parameters (translations, rotations, scale and their rates) on a selection of IGb14 reference stations*.". We do follow the same approach, except for the scale parameter: we consider translation and rotation and their rates. We do not explicitly use scale to avoid potential absorption of height signals, following Herring et al. (2016).

We shall rewrite the paragraphs cited by the Reviewer to make them clearer.

Row 244-250: This paragraph should be revised, try to better clarify what steps you did to get velocities. e.g.

1) it seems that you combine (in time domain?) daily solutions to get velocities: this is not clear enough.

2) you state the need to estimate both rotations and rotation-rates independently of EOP. It is not clear what data do you use as input in the estimation process.

3) Is the velocity/position estimated using least squares or kalman filtering?

Row 249: what solutions? velocities? positions? not clear.

Row 250: time series and velocities? are you really recomputing time series? not clear

We shall rewrite the paragraph cited by the Reviewer to make it clearer and answer the Reviewer's comments on row 244-250. We shall modify the paragraph as follows:

"To compute the velocity field, we use the forward-running Kalman filter implemented in the GLOBK module, in which the state vector includes the positions and velocities for each station (Herring et al., 2016). The input data are the daily loosely constrained solutions, as they may be freely rotated and translated, thus eliminating the need to include EOP in the state vector, and their full variance-covariance matrices. Following Herring et al. (2016), from the analysis of the previously generated time series, we retrieve the list of outliers to be excluded from the computation and the site specific parameters to model the stochastic noise on the station positions. At each epoch, the Kalman filter updates positions and velocities. With the aim of reducing the computation time, we divide the stations into sub-networks using netsel. We use a nominal number of 90 stations for each sub-network and the noise model obtained from the time series analysis. First, we estimated the velocities and positions of the stations included in each sub-network. Then, we combine the solutions obtained for each sub-network in a single solution. At the end of the forward Kalman filter run, we align positions and velocities to the IGb14 reference frame using twelve parameters Helmert transformation (rotation, translation and their rates). Velocities of stations within 1 km distance (including differently named stations at the same location) are equated in this reference frame realisation. Finally, we recalculate the time series and velocities using the values obtained in the previous iteration as a priori coordinates and expand the list of reference stations to include all the stations with random walk values lower than 0.5 mm2/yr. As reported by Herring et al. (2018), the time series that best represent the final velocity solution are those computed considering all stations in the solution as reference sites. We also express our solutions relative to the Eurasia plate as defined by Altamimi et al. (2017) plate motion model (ETRF14 reference frame) using the same procedure adopted for IGb14."

Figure 10: A few velocity vectors don't show the arrowhead, why? Please explain in the caption, at least.

The Reviewer is right. It is a problem with GMT options. We shall modify the figure to draw all the vectors' arrowheads.

I also uploaded the manuscript pdf file with a number of text editing corrections.

Thank you for your kind help. We shall modify the text accordingly